Submission for Entry:

Air Force Research Laboratory Century of Flight Award
- For Student Aerospace Research -

PROJECT TITLE:

Icing is Such a Drag: Aerodynamic Effects of Ice Accretion on Wings at Multiple Angles of Attack

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INTRODUCTION

In September, 1981, six-USAF A-10's, flying in formation at 23,000 ft, followed a KC-135 tanker on an 8 hour flight across the North Atlantic Ocean. The A-10's had been traveling through thick layers of clouds caused by a hurricane, that contained heavy precipitation, for more than two hours. The clouds contained super-cooled water droplets which had been "impinging" on the leading edges of the aircraft, creating a layer almost 1.5 inches thick of rime ice buildup on the A-10's leading edges and over the surface of the wings. The un-forecasted moderate-severe icing was so significant that each of the pilots could visually see the icing buildup on the other aircraft, as well as on their own aircraft wings. Due to aircraft performance capabilities, the flight could not climb to higher altitudes in order to escape the icing conditions. The pilots

became very concerned about their dangerous situation, which could have developed into an aircraft stall and loss of control over the freezing Atlantic, 700 miles south of Iceland. Fortunately, the A-10's had just enough excess thrust and lift available to compensate for the ice accretion and were eventually able to break clear of the icing conditions and avoid the potential loss of one or more combat aircraft. [1]

With worldwide and wartime commitments, military aircraft and crews face the probability of flying through severe weather, including icing conditions, to complete their missions. Even though military aircraft and flight crews face potentially severe weather conditions, the Air Force cannot afford to lose it's limited aircraft and aircrew resources to such hazards. "The importance of our nation's military cannot be stressed enough and the potential loss of capability due to encounters with severe weather could easily affect national security"[2]. Aerodynamic effects of ice accretion on aircraft, is still a highly experimental area of research. The more we understand the effects of icing on wings, the better we can provide pilots with information that may someday save aircraft and lives. Aeronautical engineers can also use this type of performance data to improve aircraft wing design and anti-icing equipment.

Determining the aerodynamic effects of icing on aircraft is normally conducted in specialized wind tunnel laboratories that use ice spraying equipment, like the NASA Lewis Research Center. Major wind tunnel facilities were unavailable to use on this project, so an alternative approach was developed and used to successfully determine aerodynamic effects of ice accretion. My new approach is outlined in Fig 1.

After researching the Internet, I contacted **Interactive Instruments Inc**., and after explaining my interest in aviation and my project goals, they loaned me one of their precision, low speed wind tunnels to conduct my experiment. I chose and built three different wing models that were named: 'fighter', 'transport' and 'light' aircraft, and

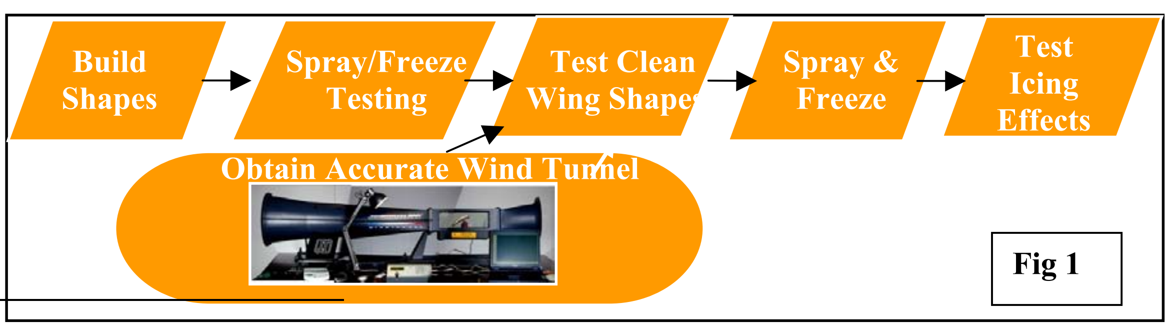


Fig 1

[1] Actual icing incident occurred and was reported to me by Lt Col John Yanaros, USAF, Ret.

[2] Maj. Gen Timothy A. Peppe, Chief of Safety Headquarters, USAF

developed a method to simulate ice accretion on them. The wings were pre-sprayed with quantitative amounts of water spray, then immediately frozen. This process was continued for several cycles. Over time, this method allowed the ice accretion to gradually build up, especially near the leading edge of the wings. Two different levels of ice accretion were generated on the wings, which were labeled: 'Light icing' and 'Moderate icing'. After the frozen wings had the selected number of spray/freezing cycles, they were tested in a 7ft long precision wind tunnel. The wind tunnel testing was conducted in my garage during cold nights, when outside temperatures were near 0 deg C to prevent the ice from melting. The 'clean wings' were also tested to provide a baseline for data comparison.

By using this wind tunnel and associated computer software, reliable performance data and graphs were obtained for each test run to include: Lift, Drag, Cd, and L/D. Note: This project generated over 900 data points, 80 graphs and charts, and dozens of digital photographs. This report is a shortened version of the complete project report due to the total page number requirement.

TERMINOLOGY

A = Surface Area of airfoil section (sq cm)
C = Airfoil chord length (inches)
Cd = Coefficient of Drag – a number used to compare different airfoil shapes and sizes.
Cl = Coefficient of Lift – a number also used to compare different sizes and shapes
ά = Angle of attack (AOA); (degrees)
D= Drag Force (kg)
L= Lift Force (kg)
NACA = National Advisory Council for Aeronautics; A number designation for each type of airfoil
Re = Reynolds number
R = Density of air (altitude)
V= Velocity (kph)
x = Chord wise position along airfoil
y = Normal position from airfoil chord line

PURPOSE

The purpose of this experiment is to quantitatively determine the aerodynamic effects of ice accretion on three different types of airfoils at different angles of attack (AOA).

HYPOTHESIS

I predict that icing on aircraft wings will decrease the lift and increase the drag overall because ice accretion on an airfoil may alter the shape and surface characteristics of the wing, which may contribute to a decrease in wing and aircraft performance.

PROCEDURE

Research Books; Internet; Encarta
Experiment - Constant Variables
– Materials
- Each airfoil made from same type of wood
- Each airfoil coated with same sealant
- Each airfoil coated with same number of coats of sealant

- Location
- Each airfoil tested in the same wind tunnel under similar temperature conditions

- Ice Layers
-Each ice layer built from same number of spraying and freezing cycles.
-Freezer was maintained at a constant temperature of -20C

- Speed
-Each test conducted from 0-80kph, all readings taken at 80kph

Experiment-Tested Variables
-Angle of Attack (AOA) - each airfoil tested at 0,10,20,30 Degree AOA
-Ice Accretion – each airfoil tested with 'No

Ice', Light Ice' and 'Moderate Ice'

Materials

Jet Stream 500 Wind Tunnel, Sony Laptop Computer, Nikon Digital Camera, Canon Video Camera, Camera tripod, Celsius thermometer, Digital gram scale, Jet Stream 500 Wind Tunnel software, NASA FoilSim software, Microsoft Picture It, PrintMaster Platinum, Adobe Photo Shop Elements, Microsoft Office 2000, Balsa wood blocks 8"x 4"x 5", Clear acrylic, matte sealant spray, Fine water spray bottle, 1 Bottle distilled water, 3 large Styrofoam cups, 1 6ft flexible pool hose section, Drinking straws, 8"x 16" red transparent plastic, Safety goggles, Work gloves, Ice cooler, 5 lbs block of dry ice.

Preparation

Before the wind tunnel arrived, I spent a month testing different airfoil surfaces, in order to find the one which would accumulate ice in the most realistic way. I tried plastic wrap, aluminum foil, and sealant spray over balsa wood airfoils. I found that the best materials were the balsa wood airfoils with the matte sealant.

Choosing and Constructing the Airfoils

From my research on the Internet, I chose three representative wing forms that include a low drag – high-speed fighter wing, a high lift – low-speed transport wing, and a low-speed light aircraft type wing. Using Microsoft Picture It, I printed out the airfoils to make cardboard templates. I used the templates to cut the three airfoil shapes out of balsa wood, using a band saw, and then sanded the airfoils down into smooth wing shapes. Each of the three templates was compared to a wing form library that contains NACA designation numbers.

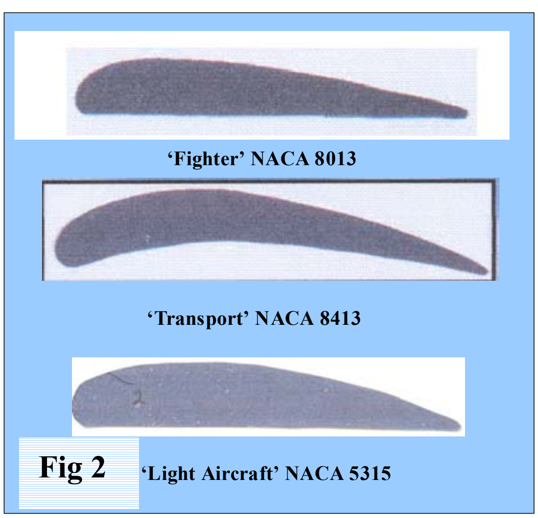


Fig 2

The airfoils were then coated with clear acrylic matte coating four times to prevent absorption of water spray. A bracket was attached to each airfoil which would connect to the mounting arm in the wind tunnel. I then calculated the surface area (SA) of each wing. The wind tunnel has sophisticated electronics, and requires SA that allows it to calculate coefficient of drag (Cd). I also used the surface area to calculate the coefficient of lift (Cl). Each of the airfoils was weighed on a digital gram scale.

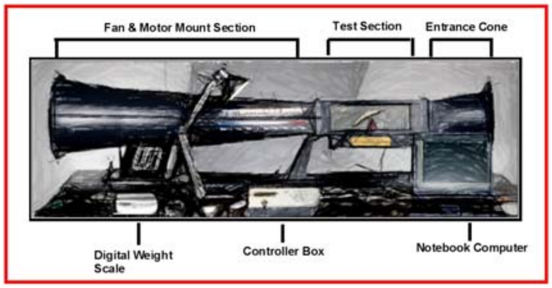
Fig 3. Testing Ice Buildup

The airfoils were sprayed 3 times using a small spray bottle with the smallest droplet spray setting selected. The wings were sprayed from a distance of six inches, centered on the leading edge of the airfoils, with each full spray producing 1ml of distilled water spray. Water droplet size generated by the spray nozzle was estimated to be 0.5mm to 1.0mm in diameter. The airfoils were placed in a freezer with the leading edge of the wing face down. The freezer temperature was adjusted to the maximum cold setting (-20C). Each time that the airfoil was returned to the freezer, it constituted 1 cycle. The number of test cycles were recorded and discussed below.

Fig 4. Wind Tunnel Assembly

The wind tunnel was setup and leveled on a long sturdy table in the garage. A notebook computer with Jetstream 500 software loaded was attached to the control box. This allowed the computer to directly control the wind tunnel settings, experiment phase and record

Fig 4



cycles. The airfoils with 'moderate' ice were then re-weighed, and a tracing made of each airfoil outline. The test runs were conducted in exactly the same way as the previous experiment

raw data. The test runs with iced airfoils were only conducted on cold nights, when outside temperatures were near or below freezing. This allowed wind tunnel testing to be completed without having the ice melt on the airfoils.

Test Procedure

Fig 5. No Ice

Each airfoil was tested 5 times for each data point with no ice at 0, 10, 20 and 30 Deg. AOA. Data was recorded by the computer and also manually recorded on a data sheet when the wind tunnel speed stabilized at 80kph. These tests were used for the base line data. Reynolds numbers were calculated for each airfoil, at 80kph.

Fig 6.'Light Ice'

Light icing was accomplished by applying 5 cycles of spraying and freezing to each airfoil, with 20 minutes between cycles. The airfoils with 'light' ice were weighed, and a tracing made of each airfoil outline with ice. The experiment was conducted in the same way as the airfoils without ice.

Fig 7. 'Moderate Ice'

Moderate Icing was applied to the airfoils by adding an additional 10 cycles of spraying and freezing, for a total of 15

Visualization Test Procedure

A wind visualization experiment was conducted by producing 'smoke' in the wind tunnel while operating it. This was accomplished by using dry ice to create a smoke effect in the wind tunnel**.** The smoke provided the ability to observe the effects of air flow as it passed through the tunnel and around the airfoil.

A 4ft section of 2in diameter flexible pool hose was connected to a bundle of drinking straws with a piece of tape. A small piece of dry ice was placed in a plastic cup inside a cooler. By adding small quantities of boiling water to the cup, the smoke was achieved. The 'smoke' flowed from the cup through the lip of the closed cooler and the pool hose to the wind tunnel. The straws on the end of the hose helped smooth and 'straighten' the smoke flow before entering the wind tunnel. A red transparent plastic filter was placed on top of the test section of the wind tunnel and all room lights were turned off except for a flashlight illuminating the test section. Test runs were conducted for clean, light and moderate iced airfoils. A Nikon Digital camera on a tripod was used to photograph each test run. Manual shutter setting of 2-30 seconds exposure were used. Adobe Photoshop Elements program was used later to enhance the visualization results.

RESULTS

The Jet Stream 500 wind tunnel documentation, states that the device is very precise, and can measure forces within the wind tunnel to less than 1%. Accuracy was crucial to this project because small changes in lift and drag due to ice accretion could make a significant difference to the test results. During this experiment, each data point was repeated five times, to reduce the possibility of errors. The average of these five test runs was then used to plot each point on the graphs.

By connecting a laptop computer installed with the Jet Stream 500 wind tunnel software to the wind tunnel, I was able to manually read data from the bottom of the computer screen as the airspeed of the wind tunnel increased in speed. The software also recorded each test run graphically on the computer screen. The graphs recorded Lift, Drag, Cd, and L/D readings as the speed increased. After the tests were completed, I was able to print out the graphs. The software allowed overlay of one raw data graph over another. I chose to use the 30deg AOA test of each wing with 'clean' vs. 'moderate ice' as my example of each of the three airfoils. This was chosen since it gave the greatest range in ice accumulation. Reynolds numbers (Re) were calculated for each airfoil under testing conditions.

The ice accretion shapes presented in Figs 8, 11 and 14 were obtained by manually tracing each set of airfoils onto graph paper before wind tunnel testing. The airfoil tracings were electronically scanned and then superimposed with the clean airfoil shapes into a grid format in MS Excel. This process was also manually accomplished by using tracing paper. The original ice shape tracings were used to assist in fine tuning the correct shapes. These two dimensional graphical plots of the airfoil cross-sections use a format used by NASA, which plots the cross-section as a function of a percentage of airfoil chord length.

Test Results for the 'Fighter Aircraft' (NACA 8013) Airfoil

Figure 8 depicts the ice tracings for the NACA 8013 airfoil. These were done to capture the main features of the icing along the surfaces of the airfoils. Each of the tracings show two primary ice forms: 1) minor ice forms that built up along the upper and lower surface and 2) a longer main ice build up on the airfoil

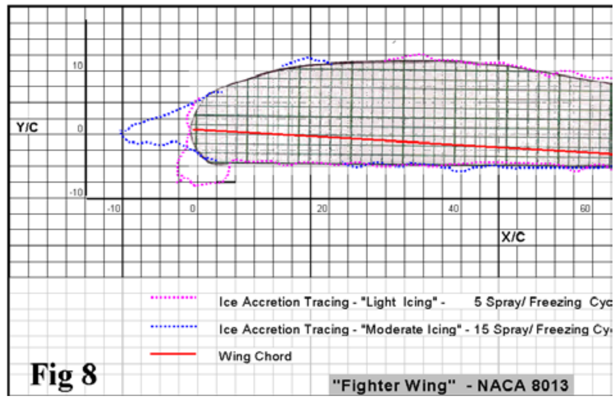


Fig 8

leading edge. For 'moderate icing', this structure grew significantly. Fig 9 shows a 63% decrease in lift at 20 deg AOA for 'moderate' ice vs. the 'clean' wing.

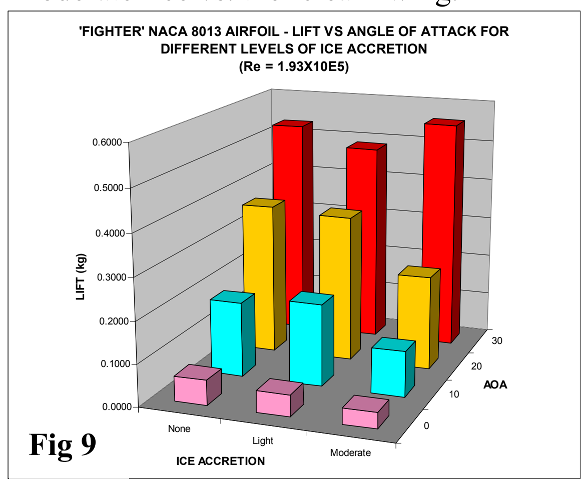


Fig 9

For the 'clean' configuration, drag increased (approx. 300%) for each 10-degree increase of AOA from 0-30deg. As ice accumulations were increased to 'light ice', the difference in drag for each AOA remained similar to the drag of the 'clean' airfoil. For 'moderate

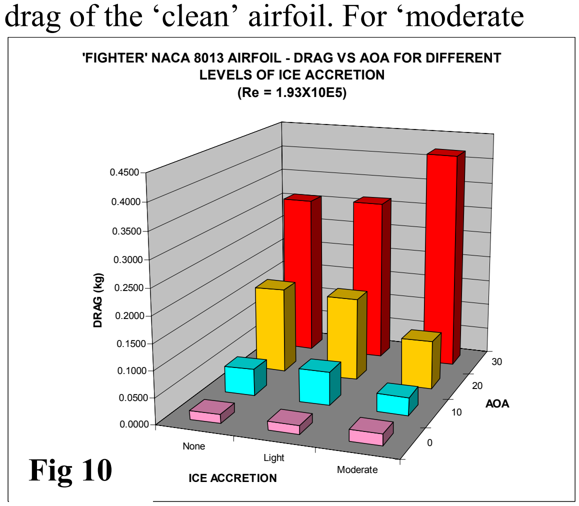


Fig 10

icing' there was less drag at 10deg and 20deg. AOA, (Fig 10) than the 'clean' airfoil. At 30deg. AOA the drag force doubled from 20deg. AOA. At 30deg AOA, the lift performance was greater than either the 'clean' or 'light icing' airfoil. The maximum L/D for all three icing conditions was 10 deg. AOA. L/D performance was approx. 50% less at 0 deg. AOA with 'moderate icing', than with either 'clean' or 'light icing'.

Test Results for the 'Transport Aircraft' NACA 8413 Airfoil

Figure 11 presents a 2-dimensional view of NACA 8413 airfoil with both levels of ice accretion. Clear ice developed over almost the entire surface area. A large horn developed on the airfoil leading edge, and became very prominent for 'moderate icing'. At all

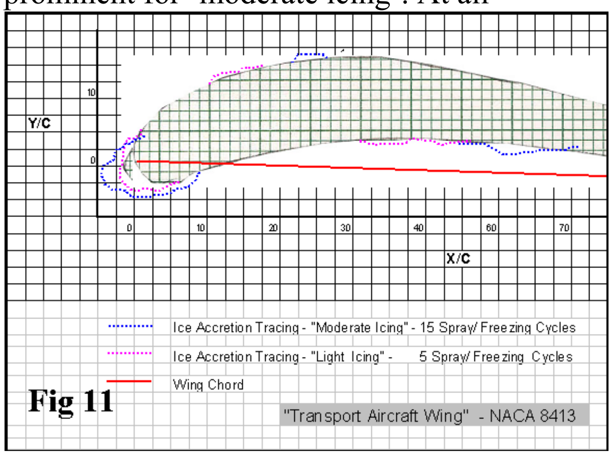


Fig 11

measured AOAs, the 'Transport' airfoil had better lift performance than the other two airfoils with 'moderate' ice (Fig17). Raw data

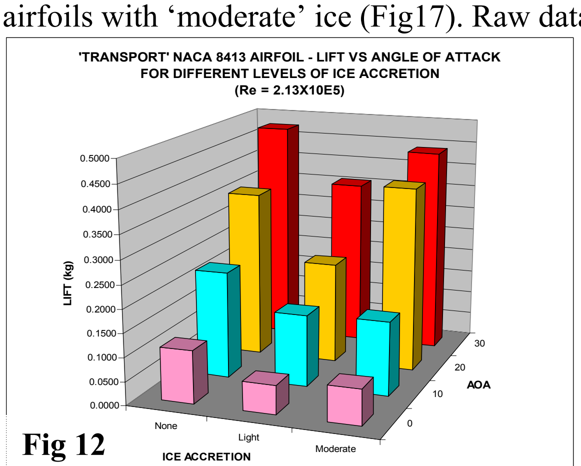


Fig 12

graphs show that as the airspeed increased to 80kph, the lift performance of the 'clean' and 'iced' airfoil remained almost the same. Drag on the airfoil with ice accretion increased with airspeed. What was surprising in the 'Transport' airfoil data (Fig 13) was that drag actually decreased from 'clean' to 'light icing' by up to 50%. The 'light icing' surface probably had less drag because it had less surface friction than the wooden surface.

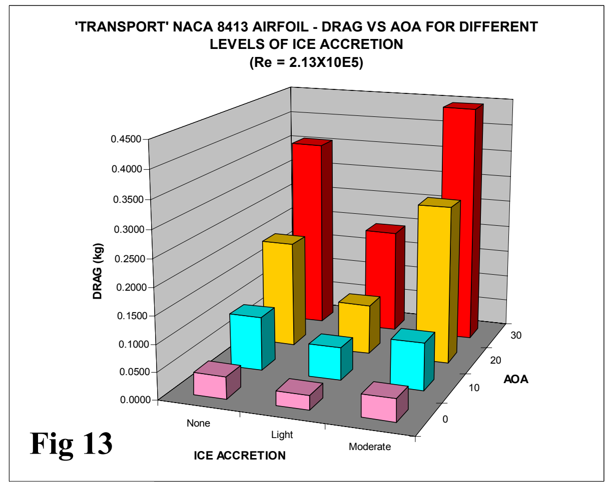


Fig 13

Test Results for 'Light Aircraft' NACA 5315 Airfoil

Figure 14 depicts the ice tracings for the NACA 5315 airfoil. For 'light icing' conditions, ice accretions built up around the leading edge and along the bottom surface of

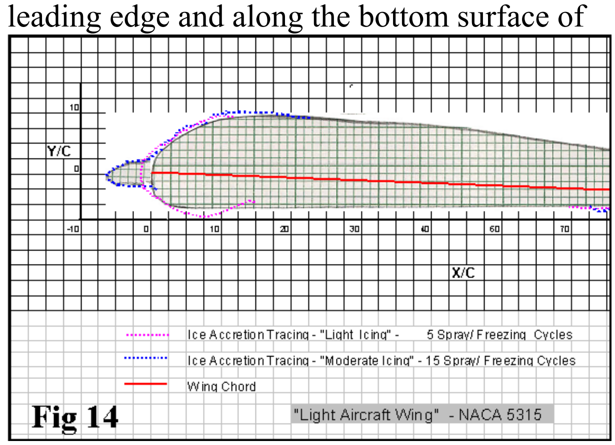


Fig 14

the airfoil. For the 'moderate' ice conditions, a large horn developed on the leading edge. For the 'Light Aircraft' airfoil, after passing 20kph, the lift performance of the 'moderate iced' airfoil started to drop and the drag

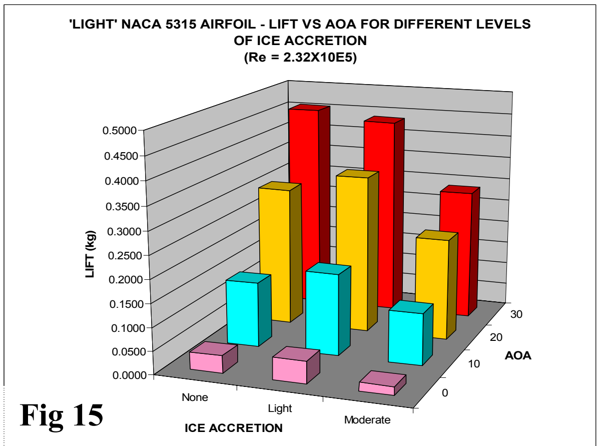


Fig 15

increased significantly, when compared to the ‘clean’ airfoil. There was a 60% drop in lift performance in the airfoil with ‘moderate ice’ at 20deg AOA.

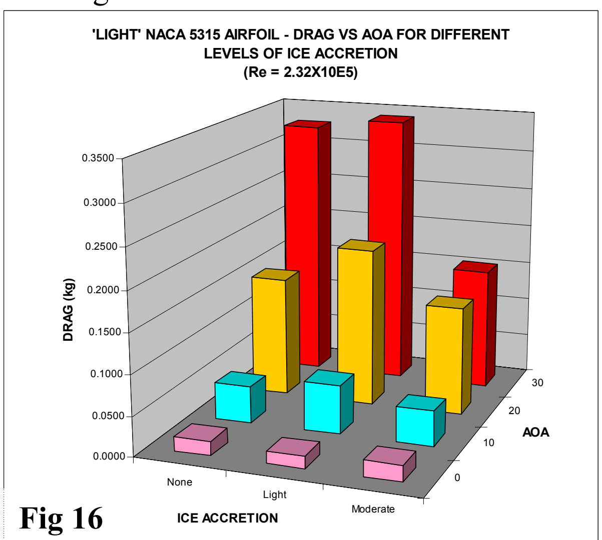


Fig 16

There was a 55% reduction in drag, from the ‘clean’ wing at 30deg. AOA to the ‘moderate iced’ wing (Fig 16). The reduction in drag was offset by a similar decrease in lift performance (Fig 15).

Airfoil Performance Comparisons

After observing the effects of icing on each of the three types of airfoils, I wanted to determine how these airfoils compared with each other. Coefficient of Drag (Cd) and the Coefficient of Lift (Cl) are used to compare the relative performance of different sized and shaped wings. Fig 17 compares the Cl for each airfoil at different AOA’s. The ’Transport’ NACA 8413 airfoil has a better lift

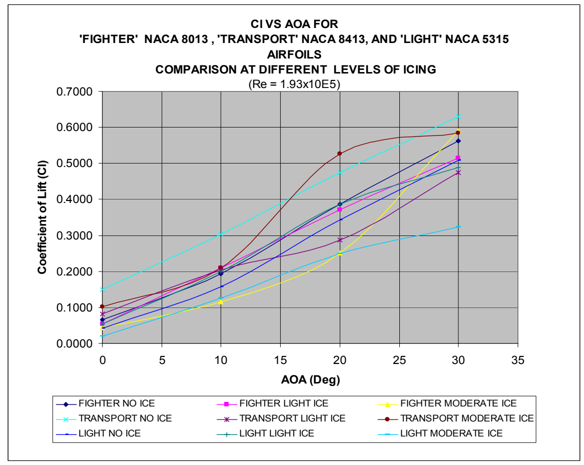


Fig 17

performance for most conditions than the other two wings. This was expected since it was designed to be a high-lift wing. The ‘Light’ NACA 5315 airfoil had a higher lift coefficient in all cases with ‘light icing’ than without icing. But as icing increased from ‘light’ to ‘moderate’, the ‘Light Aircraft’ NACA 5315 Cl dropped off significantly, as expected. The Cl was lower for the ‘Light Aircraft’ NACA 5315 airfoil than the other two under almost all conditions. The ‘Transport’ NACA 8413 airfoil’s Cl curve was inverted compared to the other two airfoils. This was because the Cl for the ‘Transport’ airfoil actually increased for ‘moderate ice’ and for AOAs 0-20deg. This was not expected, but is likely a result of it’s radically different camber and shape compared with the other two airfoils. Fig 18 shows the test comparison

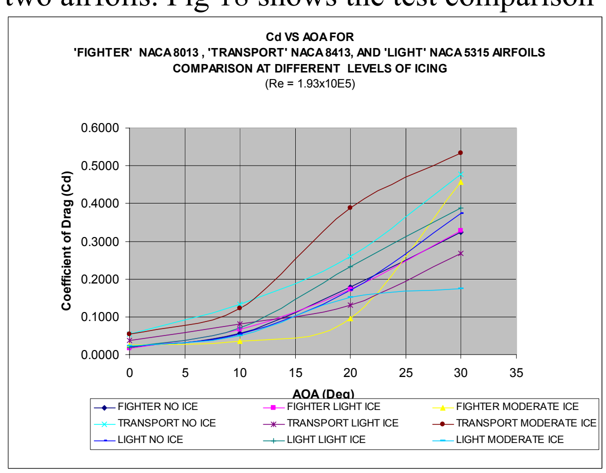


Fig 18

of the three airfoils by drag coefficient (Cd). At most AOAs, the 'Transport' NACA 8413 airfoil had a much higher Cd than the other airfoils. The only exception was for 'light icing' at high AOAs. The 'Fighter' NACA 8013 airfoil and the 'Light Aircraft ' NACA 5315 airfoil actually had less drag for 'moderate icing' at 10 and 20deg AOA than they had for the 'clean' airfoil and 'light icing'.

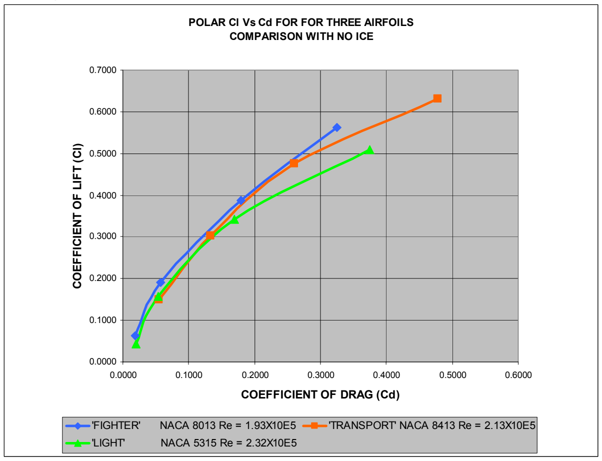


Fig 19

The CL/CD graphs for each of the airfoils were plotted to compare their performances (Fig 19) The 'Fighter' NACA 8013 airfoil had better aerodynamic performance than the other airfoils, especially at lower AOAs. The most efficient AOA for all three airfoils was 10deg

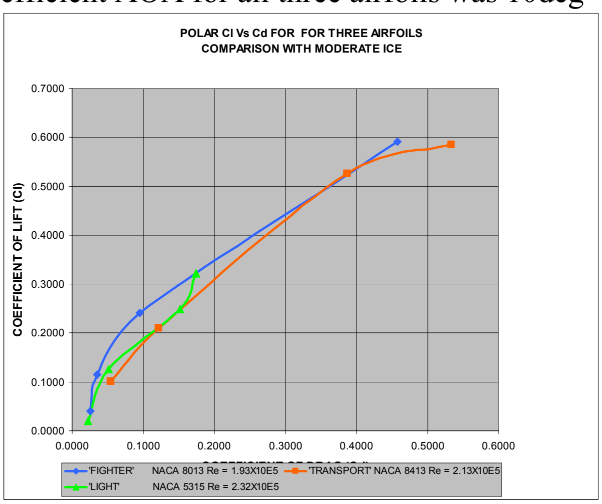


Fig 20

AOA, where CL/CD Max was obtained at all icing conditions. The worst conditions for all three airfoils were with 'moderate icing' and at 30deg AOA. Figure 20 shows the relative performance loss due to 'moderate icing' as compared to the 'clean' wing results in Fig 19. Drag becomes a major factor in the loss of performance for the 'Fighter and 'Transport' wings. The 'Light Aircraft' wing was much more affected by the loss of lift performance than the other wings.

Visualization Test Results

Wind tunnel engineers sometimes use smoke to visualize the wind flow around the airfoil. The 'smoke' effect was created in this experiment by using dry ice. Several test runs using dry ice were accomplished at the 20kph wind speed setting. Higher wind speeds would have caused the smoke to become turbulent in the test section. With the room lights out, different lighting conditions and filters were applied to the top of the glass test section. The best visual results were obtained by shining a flashlight and using a red transparent plastic filter on top of the test section. The

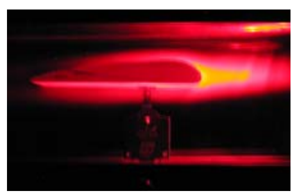


Fig 21a (Original)
'Light Aircraft'
NACA 5315
0 deg AOA
No Ice

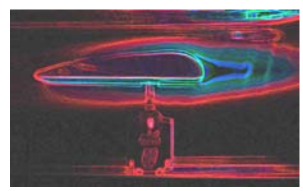


Fig 21b (Enhanced)
'Light Aircraft'
NACA 5315
0 deg AOA
No Ice

Fig 21c (Original)
'Light Aircraft'
NACA 5315
0 deg AOA
Moderate Ice

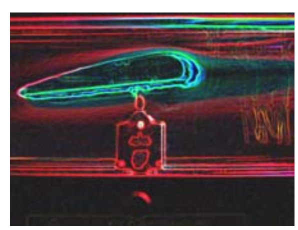


Fig 21d (Enhanced)
'Light Aircraft'
NACA 5315
0 deg AOA
Moderate Ice

combination of the red filter and the yellow light highlighted the ice buildup on the airfoil (Figs 21a and 21c). On each of the photographs, flow visualizations can be seen as ‘smoke’ flows around each of the airfoils.

Comparing the sizes of wakes for clean airfoils with ‘moderate icing’, the wake near the leading edge for the clean airfoil is slightly smaller than the wake for the ‘moderate iced’ airfoil. This is a sign that there is less drag. Figs 21a-d show a point where smoke no longer follows the upper curvature of the airfoil. On an aircraft, it is critical that the flow stays attached to the airfoil. If the AOA is too steep or disrupted by icing, the flow separates early (towards the leading edge of the airfoil) and there is a loss of lift, which can stall the aircraft. Figure 21a and b are the same picture of a clean wing at 0deg AOA , which shows flow separation from the top surface at 80% of the length. Fig 21c-d shows the same wing with moderate icing with separation near 50% of the length. This relative percentage change compares to the 50% loss in lift performance for the ‘Light Aircraft’ airfoil with ‘moderate icing’.

CONCLUSIONS

This project has proved that my hypothesis was correct. Under controlled conditions, this experiment attempted to simulate and compare two different levels of ice accretion on three different aircraft type wings, to the same wings without icing.

Three different airfoils underwent 5 water spray/freezing cycles for the ‘light’ clear icing configuration and 15 spray/water cycles for the ‘moderate’ clear icing conditions. During wind tunnel testing at 80kph, each test was repeated 5 times for each of the 0, 10, 20, and 30deg AOA settings, at each icing condition. The averages of these data points were used to plot graphs that compared aerodynamic performance of each airfoil for different icing conditions. The wind tunnel test runs produced more than 900 data points, which were used to create 48 charts and graphs that analyzed the performance of all three wings. Thirty-six raw data graphs were also produced using the Jet Stream 500 Windows software to confirm the data. The accuracy and repeatability of each test was checked and confirmed. The results clearly show that lift performance is reduced significantly with more than light ice accretion on all three airfoils. ‘Moderate icing’ on airfoils decreases lift by as much as 25%. Lift increased as AOA increased for all airfoils, but under ‘moderate icing’ conditions, lift performance drops off except for the ‘Fighter’ NACA 5315 airfoil. The drag coefficient increased 80% for the ‘Transport’ airfoil and 30% for the ‘Fighter’ airfoil as AOA increased from 20-30deg with ‘moderate’ icing. Under the same conditions, the ‘Light aircraft’ NACA 5315 airfoil had a decrease in drag, but it was offset by a lift coefficient that was 50% lower than the other two airfoils. By studying the visualization results, ‘moderate icing’ disrupted the streamline flow and created a significant drag penalty. The visualization results also show that the wake around the leading edge of the wing for ‘moderate icing’ is much wider, which indicates more drag. Early flow separation at the top of the wing confirms a loss of lift with icing.

Finally, by looking at the data for ‘moderate icing’, the ‘Transport NACA 8413 airfoil had the worst L/ D performance of the three wings. A light aircraft should remain clear of icing, especially at 20-30deg AOA, where that wing may have as much as a 50% decrease in lift performance with moderate clear icing and little excess power to spare. Power would be needed to compensate for the added drag force due to the ice accumulation, the weight of the ice, and for the loss in wing lift performance. The ‘Fighter’ NACA 8013 airfoil demonstrated the best overall performance of the three airfoils in most icing conditions. The fighter aircraft should also have the most

power available to compensate for lift and drag performance penalties due to icing. But, the aerodynamic performance of all three airfoils was significantly degraded by ice accretion, which could lead to aircraft stall or catastrophe.
Finally, this project has clearly presented a very cost effective real-world application of current technology that could impact both current and future Air Force capabilities.
Every aircraft and crew that is lost to weather-related conditions is not only a tragic loss, but affects the operational capability of the Air Force. By better understanding the effects of icing, both aircrews and engineers can make more informed decisions during this new century, and avoid repeating the mistakes that have led to many icing-related aviation losses over this **first century of flight**.

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